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Developments in technology cost drivers – dynamics of technological change and market forces

Jenny Hayward and Paul Graham

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Enquiries should be addressed to:
Paul Graham
CSIRO Energy Transformed Flagship
PO Box 330, Newcastle NSW 2300
Phone: +61-2-49606061
Email: paul.graham@csiro.au

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1. EXECUTIVE SUMMARY

The process of technological change is often expressed as an experience or learning curve, where the cost of the technology decreases by an historically measured percentage (learning rate) for every doubling of cumulative capacity or output. As more capacity is installed in the future, the cost can be projected to fall over time. However, recent experience of increased real power plant prices has reminded us that other drivers can at times exert a stronger influence on the price trajectory.

In seeking to understand recent technology price increases, one possible explanation explored is whether a revision of bottom-up engineering costs had occurred due to new information about the real costs of building first of a kind plant. However, given that the price increases have occurred across not just emerging but also mature technologies for which there are decades of plant construction experience, this explanation does not appear plausible.

The data from two case studies explored in this paper strongly supports the proposal that market forces have been the main driving force behind the increased cost of electricity generation technologies. Market forces come in two separate but related guises. The first is changes in raw material costs used in construction of the power plant. The second is where there is a supply-demand imbalance in the market for the power plant itself. These effects can be difficult to distinguish from one another when demand for a power plant is strong, affecting both the power plant and raw material markets.

These power plant market forces which in the past five years have manifested as a price bubble on top of the ordinary cost curve could equally manifest as a price dip if circumstances contrived to create a depressed market for power plants and their raw materials. It is also very difficult to predict how long a “bubble” or “dip” might last. There might also be cause to believe some price changes might be permanent due to fundamental changes in market structure (e.g. extended minerals shortages).

The presence of such uncertainties around the effects of market forces creates a challenge for cost forecasters. If a price bubble is suspected, it is important to have a methodology for eventually adjusting the price back down to the underlying cost curve. Otherwise the future price of the technology may be over-estimated.

2. INTRODUCTION

In the study of future technology costs, the conventional assumption is that technologies will cost less (in real terms) in the future due to learning and experience, encompassing factors such as technological change and economies of scale. However, contrary to expectations, the costs of most electricity generation technologies have increased in real terms in the past five years. This briefing provides a discussion of the factors behind this phenomenon and their implications for expectations of future costs. The report was prepared as input to the Garnaut Review Update in a relatively short time frame, and therefore is not intended to be comprehensive.

3. DRIVERS OF COST REDUCTIONS: TECHNOLOGICAL CHANGE AND EXPERIENCE CURVES

The phenomenon of “technology learning” has been observed for the development of new technologies and processes since the 1930’s when it was noted by Wright for airplane production (Wright, 1936) and later more extensively by the US Air Force for airframe production (Alchian, 1949, Hirsch, 1956). The term “learning-by-doing” was coined by Arrow (Arrow, 1962) and was used to explain the effect increasing the knowledge or experience of the labour force had on the economics of production of technology and processes (improvements in per capita income).

Grübler et al (1999) discussed and demonstrated how technology learning and diffusion for energy technologies can be incorporated into economic models of electricity generation. (Schrattenholzer and McDonald, 2001) calculated experience curves and rates of learning for many energy-related technologies as, up until then, learning rates from other technologies (Dutton and Thomas, 1984) were being used.

Technology learning is typically represented in the form of an “experience curve¹”, where unit costs of a technology or process decrease by a certain percentage (the learning rate) for every doubling of cumulative capacity or output i.e.

$$IC(CC) = IC(CC_0) \times CC^{-b} \quad (0.1)$$

where $IC(CC)$ is the investment cost of a technology at CC cumulative capacity, $IC(CC_0)$ is the investment cost at CC_0 unit cumulative capacity, and b is the learning index. The learning index is related to the learning rate LR by the following equation:

$$LR = 100 - 2^{-b} \quad (0.2)$$

¹ Experience curves are also commonly known as learning curves. We have used the term experience curve as defined in INTERNATIONAL ENERGY AGENCY (2000) Experience curves for energy technology policy. Paris, France OECD.

where LR is represented as a percentage of cost.

However, gaining of knowledge or experience is not the only factor that results in cost reductions, economies of scale, convoy effects and driven investments can also reduce costs. Four broad factors that can influence the slope of an experience curve have been identified (International Energy Agency, 2000):

- Positive changes in the technology, termed “technology structural changes” lead to a sharp decrease in the experience curve (increased rate of learning, thus sharp increase in b and resultant decrease in the investment cost IC) over a short period of cumulative capacity increase, where learning switches from one curve (or rate of learning) to another.
- Market shakeout, which happens when price is observed instead of cost, can also result in a sharp increase in the learning rate. A shakeout can be observed after the early stages of the development of a technology. When more competitors enter the market, the price umbrella the original manufacturers held when they were exclusive suppliers is lost and the price returns closer to the marginal cost curve cost (Staff of the Boston Consulting Group, 1968). This has little to do with learning since it may represent little or no change in costs. However, more often only price data is available and consequently this phenomenon can have significant impact on construction and application of learning curves.
- Government policy and research, development and demonstration project spending can affect the slope of the realised learning curve by accelerating the learning process via accumulation of knowledge and experience. Policies can also influence the choice of technology, through mandates for a percentage of renewable energy by a given date, emissions trading schemes, feed-in tariffs, tax concessions etc.

Finally, observed experience curves for a whole technology are a compounded effect of experience curves for different and interacting parts of a technology. For example, PV installations are made up of PV modules and the balance of system (BOS) which includes the inverter. These are reported to have quite different learning rates and may be sourced globally (particularly the module) while the BOS is often sourced locally (Shum and Watanabe, 2008, International Energy Agency, 2000, Junginger et al., 2005)

4. DRIVERS OF COST INCREASES: ENGINEERING ADJUSTMENTS AND MARKET FORCES

Higher prices have been observed in recent times across the board for electricity generation technologies. For example, Figure 1 shows CSIRO cost estimates for various technologies over different years of publication which show a general increasing trend. Note that the years of publication are shown in order on the x-axis but are not consecutive. This upward trend in current costs is also evident in the

comparison of cost assumptions included in the 2007-08 Garnaut Review and the 2011 Garnaut update (Burgess 2011).

For emerging technologies such as post combustion capture, the price increases could potentially be explained by adjustments of the engineering view of what it will cost to build such a plant. In the early stages of a technology there can at times be some excessive optimism about what it costs to build a new type of plant. Until the first plant is built a thorough knowledge of all the potential capital costs is not possible. As the technology comes closer to being deployed, more accurate engineering bottom-up cost assessments are performed and subsequently an upward revision in the capital cost estimate can occur.

However, the data shows that mature technologies such as wind and sub/super critical black coal plant also have experienced an upward price trend. Therefore engineering adjustments can be ruled out as the major cause of the recent cost increases, although it could have been a contributing factor for some technologies.

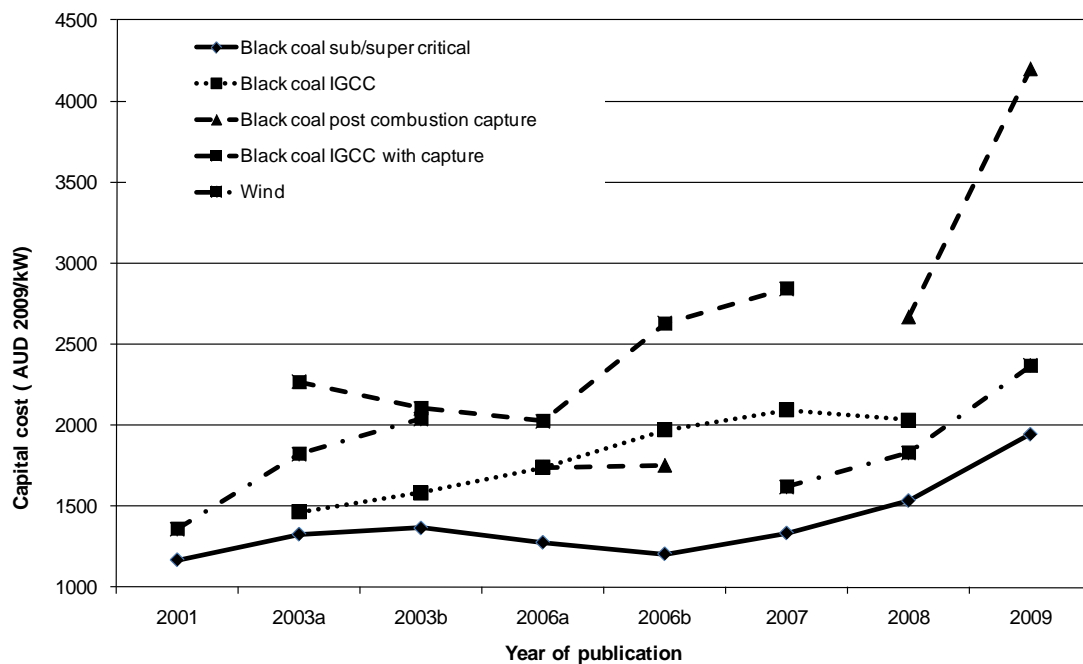


Figure 1: Change in CSIRO current electricity generation plant price estimates. Data from (Graham et al., 2008, Reedman et al., 2008, Reedman et al., 2006b, Reedman et al., 2006a, Graham et al., 2003, Graham and Williams, 2003, Cottrell et al., 2003, Graham and Williams, 2001, Dave et al., 2008)

Given that the phenomenon occurs across both mature and immature technologies, market forces are a far more likely driver. By market forces we mean the global market for the technologies themselves and the raw materials used in their production. To examine this issue more closely we examine two case studies: wind and solar photovoltaics.

4.1 Case study 1: wind power cost increases

It can be seen in Figure 2 that the price of wind turbines and their installation increased from 2004-2005 up until 2008. With the wind industry expanding at up to 25% per annum in recent years wind power prices have moved in the opposite direction to what “learning by doing” would suggest.

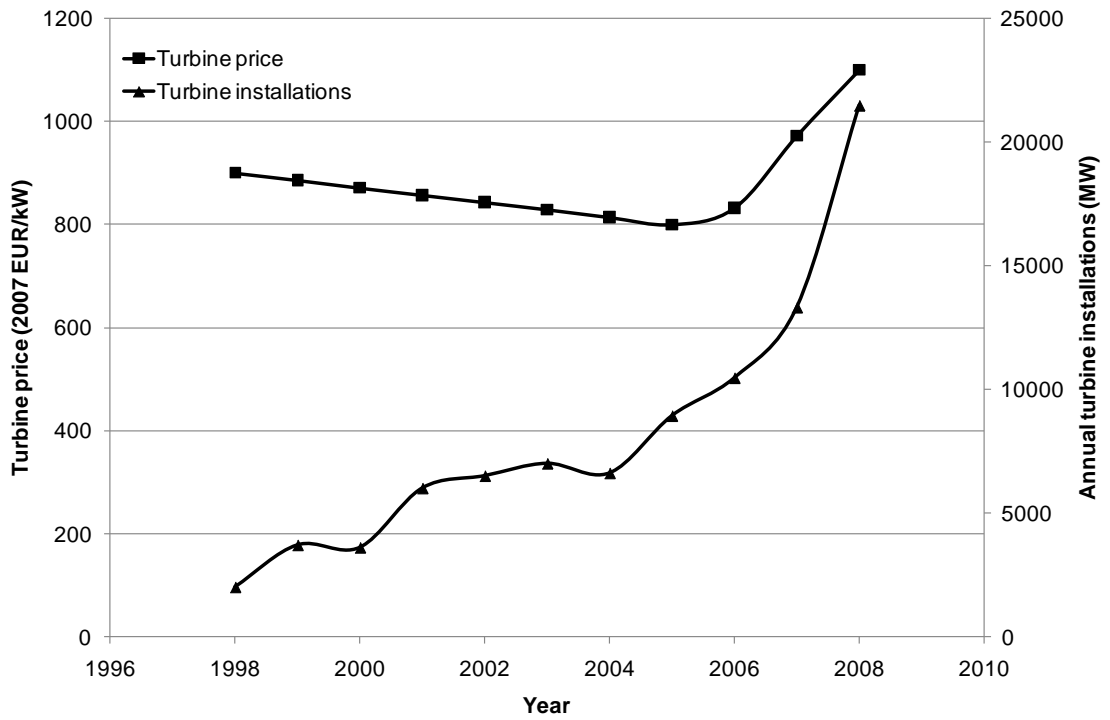


Figure 2: Wind turbine price and annual installations in IEA countries. Data from (International Energy Agency, 2000-2009)

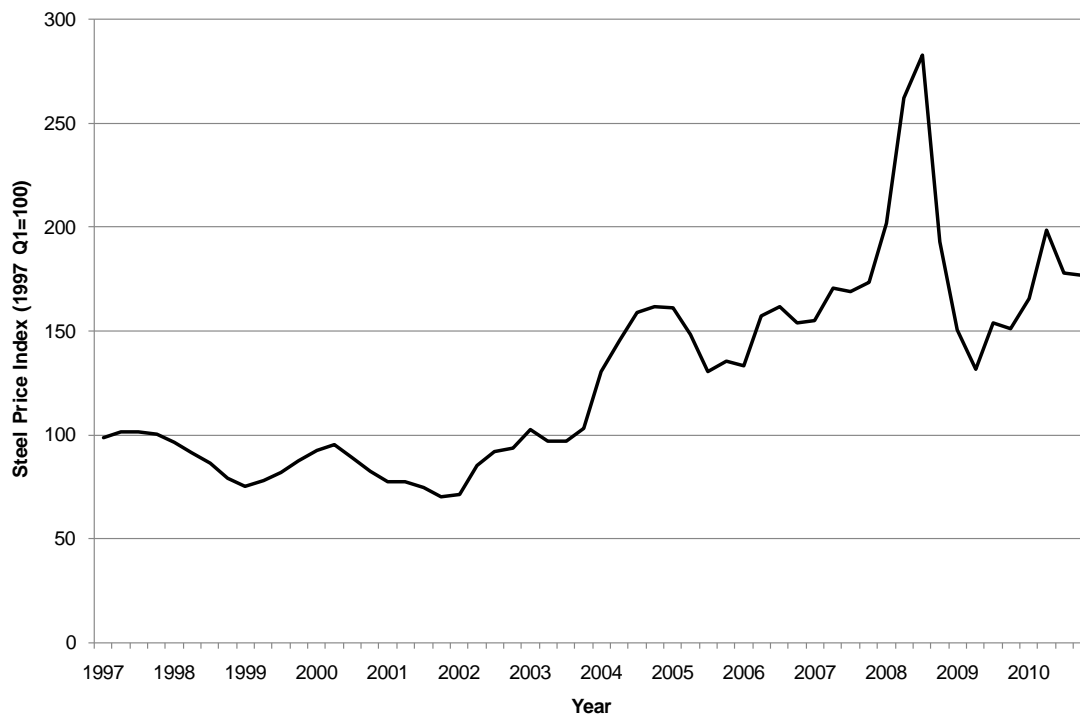


Figure 3: Steel price index. Data from (CRU, 2010)

The higher prices are partly the result of increasing input material prices and labour shortages. Prices of raw materials such as steel have increased considerably, approximately two years before the observed increase in wind turbines. For example, steel prices increased by ~150 points or 117% in the period from the first quarter of 2004 to the third quarter in 2008 which is the peak (Figure 3).

In the view of (Milborrow, 2008) , whilst raw materials prices have been a factor, a major part of increased prices is profit-making by the wind plant manufacturing industry. The wind industry faced significant losses at the end of 2004 and so has been restoring profitability. To test his hypothesis, Milborrow determined the amount of steel in a typical wind turbine and by applying the increase in steel price to the amount of steel he was unable to explain the large jump in wind turbine prices. Labour prices had also been increasing, which can explain a part of the difference.

Profit taking, where prices rise above costs inclusive of normal profits, is possible if there is extremely high demand for a product (which appears well founded in the case of wind) and new or existing suppliers cannot readily expand supply.

The main constraint for expanding supply is the need to expand their manufacturing facilities. Such facilities are usually planned several years ahead and take more than a year to complete construction. It is likely that the wind industry did not anticipate how fast demand would grow and consistently under-invested in wind plant manufacturing facilities over a number of years.

If high demand growth and underinvestment in wind plant manufacturing facilities does explain the ability of wind plant suppliers to demand higher prices, one would expect

prices to eventually fall as supply catches up with demand. This would represent a “price bubble” cycle. Unfortunately, the data is insufficient to observe a full price bubble cycle for wind. However, this can be observed in the next case study.

If a price bubble has occurred then prices for wind turbines should theoretically start to ease in the near future, and may already have done so according to some reports as demand in Europe and North America in 2010 was not as great as predicted, due to the economic downturn and changing policies in those countries. However, the market could still remain tightly balanced, with the International Energy Agency raising its forecast for wind capacity from 231 GW to 415 GW by 2015 (Buddensiek et al., 2010, Iken, 2011).

The recent trend in China is different. China has an aggressive policy to have an installed wind capacity of 100 GW by 2020 and in order to meet this target the market has been doubling every year since 1999. However, China has policies which mean it must use internally-manufactured turbines and thus it sits outside of the global market (Koenemann, 2010).

4.2 Case study 2: solar photovoltaic cost increases

Photovoltaics are a technology which perfectly demonstrates the price “bubble” effect as the data indicates it has completed this cycle once in recent years. Figure 4 shows global photovoltaic module installations per year versus price of modules and the industry’s production capability. The production capability has two components: production from IEA countries (includes Europe, Japan and USA) and production from non-IEA countries. It can be seen that as demand, driven mainly by Spain and Germany’s renewable policies, began to exceed supply in the year 2005, production facilities gradually came online in the non-IEA countries and over time as supply from those countries exceeded that from the IEA the price of photovoltaic modules dropped dramatically (International Energy Agency, 1993-2009).

The price of modules has arguably moved back towards the underlying cost curve as represented by a learning curve, which is governed by a ~20% reduction in cost of modules for every doubling of cumulative capacity installed (Neij, 2008).

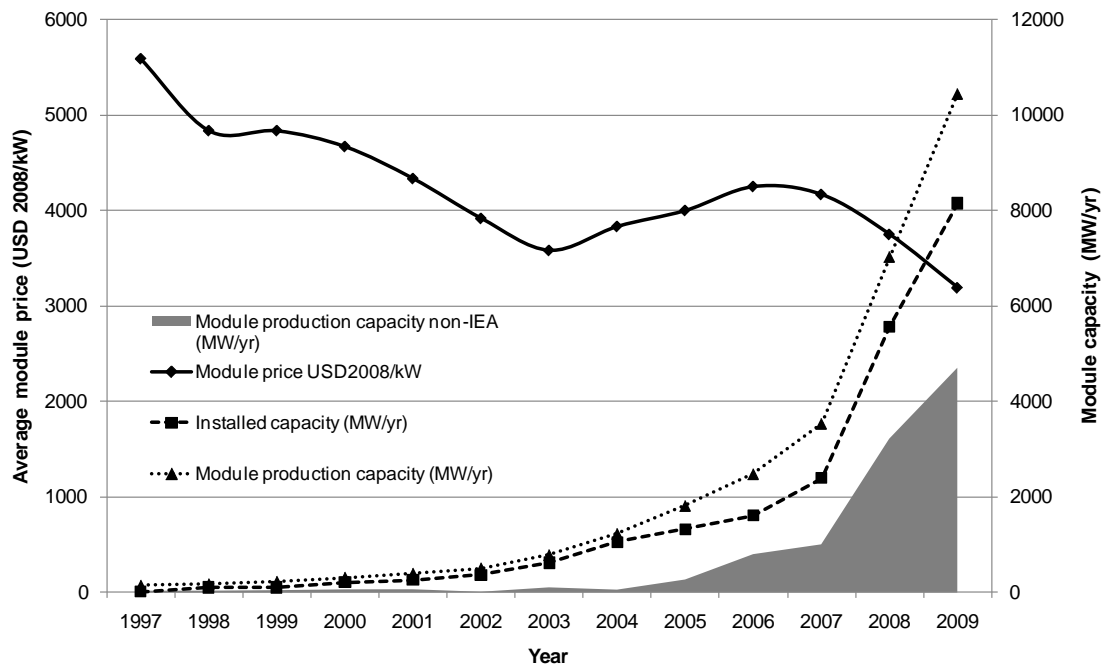


Figure 4: Photovoltaic module price and capacity trends (Data from (Energy Efficiency and Renewable Energy, 2010, Jäger-Waldau, 2010, European Photovoltaics Industry Association, 2010, International Energy Agency, 1993-2009)

The majority of modules are made from silicon cells, which rely on a supply of solar-grade polysilicon. There were global shortages of polysilicon during the years 2005-2009, until more facilities could be constructed to process the silicon. This can be seen in Figure 5, where the price of modules is shown versus polysilicon demand from the photovoltaic and semiconductor industries. Also shown is the spare stock of polysilicon per year, which has been negative since the year 2003². It can be seen from Figure 5 that the supply shortfall was driven by the high demand for photovoltaics (Braga et al., 2008, Energy Efficiency and Renewable Energy, 2010). Thus, not only were there shortages in module production but also silicon production. During this period of time the price of solar-grade silicon on the spot market was extremely high. It is difficult to obtain reliable estimates of silicon spot prices and contractor prices; according to one industry report, the price reached a peak of ~400 \$/tonne in 2008 (Voith, 2009). However, as most silicon is sold on contracts to the solar industry that spot market prices have tended to overstate the average purchase price (Energy Efficiency and Renewable Energy, 2010).

² Negative stock indicates the amount by which sales exceeded production in a given year

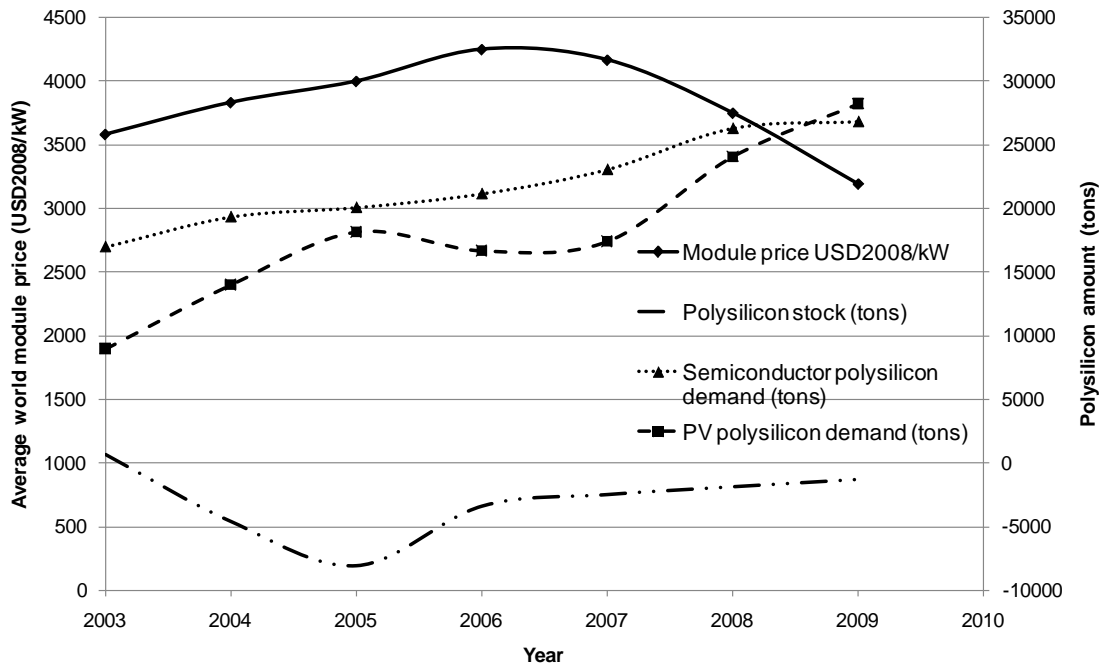


Figure 5: Photovoltaic module price and silicon stock and demand trends (Data from (Braga et al., 2008, Energy Efficiency and Renewable Energy, 2010)

Prices of photovoltaics are expected to continue their current declining trend as further expansions are planned in both module production and solar-grade silicon supply. Most of the planned capacity expansions are in China. Also, producers in South Korea are planning on almost doubling their capacity, but they are starting from a much smaller base (International Energy Agency, 1993-2009, Jäger-Waldau, 2010, Iken et al., 2010). This means that as long as demand does not increase dramatically, supply should be able to keep up with demand and the price of modules should continue to fall.

5. CONCLUSION AND IMPLICATIONS

The assumption that as learning or experience accumulates for a technology, the price will continue to decrease is the basis for most electricity generation cost projections. And rightly so. It provides an auditable, quantifiable means of projecting costs forward on the basis of past observed learning. However, recent experience of increased real power plant prices has reminded us that other drivers can at times exert a stronger influence on the price trajectory.

In seeking to understand recent technology price increases, one possible explanation explored was whether a revision of bottom-up engineering costs had occurred due to new information about the real costs of building first of a kind plant. However, given that the price increases have occurred across not just emerging but also mature technologies for which there are decades of plant construction experience, this explanation does not appear plausible.

CONCLUSION AND IMPLICATIONS

The data from two case studies explored in this paper strongly supports the proposal that market forces have been the main driving force behind the increased cost of electricity generation technologies. Market forces come in two separate but related guises. The first is changes in raw material costs used in construction of the power plant. The second is where there is a supply-demand imbalance in the market for the power plant itself. These effects can be difficult to distinguish from one another when demand for a power plant is strong, affecting both the power plant and raw material markets.

The levelised costs of renewable technologies are particularly vulnerable to market forces since they have a large capital component in their total levelised costs and their plant manufacturing base is smaller than that of more mature technologies.

For wind power it appears that a lack of manufacturing facilities to keep up with incredibly strong growth of around 25% per annum was the main driver of price increases. Solar photovoltaics faced similar price pressure, mainly in regard to polysilicon production. However, by increasing production facilities, particularly in China, of both modules and polysilicon, the demand for photovoltaic modules has been met and the prices have fallen from their peak in 2006-07. China is not part of the global market for wind turbines as they have an aggressive domestic policy for wind plant installation but globally wind prices may have eased somewhat recently due to lower than expected demand in Europe and North America. On the other hand, prices for raw materials such as steel have not yet fully declined to their pre-2006 levels.

These power plant market forces which in the past five years have manifested as a price bubble on top of the ordinary cost curve could equally manifest as a price dip if circumstances contrived to create a depressed market for power plants and their raw materials. It is also very difficult to predict how long a “bubble” or “dip” might last. There might also be cause to believe some price changes might be permanent due to fundamental changes in market structure (e.g. extended minerals shortages).

The presence of such uncertainties around the effects of market forces creates a challenge for cost forecasters. If the current increase in costs is a permanent development (i.e. not a temporary scarcity premium) then future changes in costs should be estimated by accepting current prices as the true underlying cost and starting the adjusted historical learning curve from that point onwards. However, if it is not a cost but a price increase (as proposed in the two case studies), then when more manufacturers come onto the market and supply can catch up with demand, the price can be expected to drop closer to the “real” cost level. As can be seen in Figure 6, if a temporary price increase is suspected, it is important to have a methodology for adjusting the price down. Otherwise the price of the technology may be over-estimated in the long term (Hayward et al., 2011).

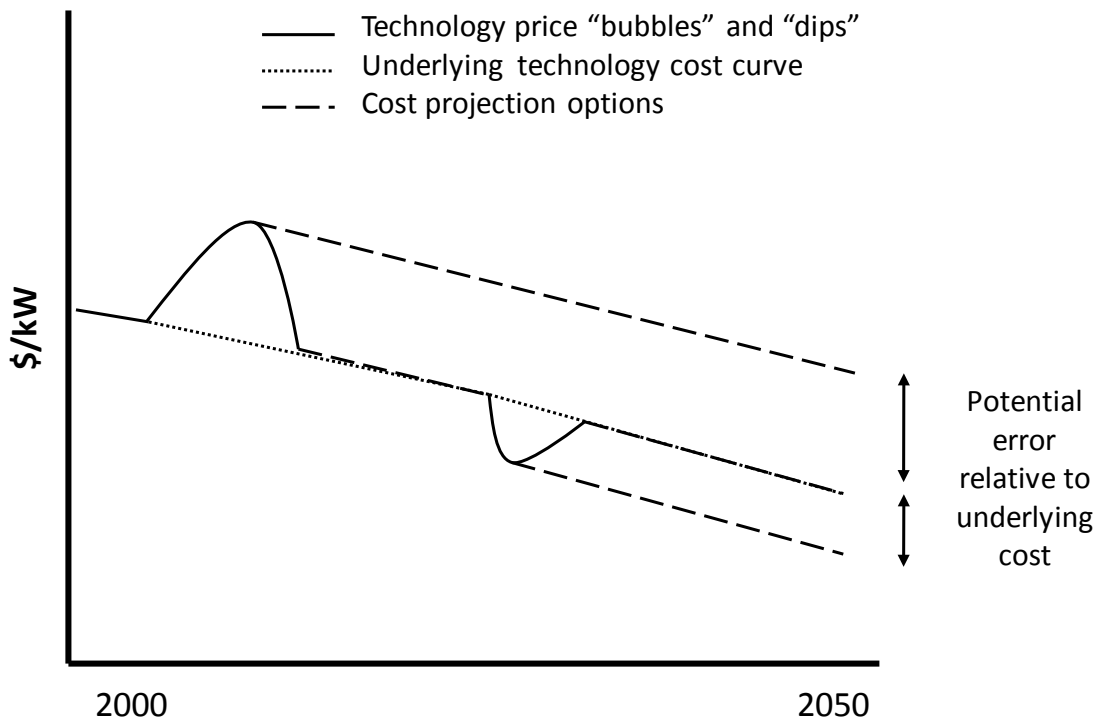
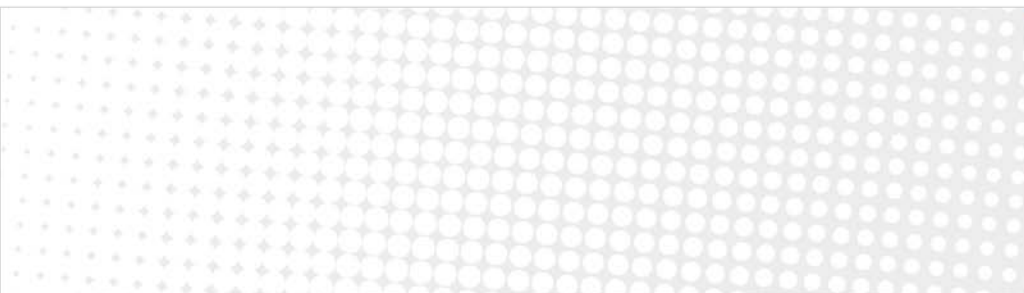


Figure 6: Options for forecasting technology prices during a price bubble or dip phenomenon

REFERENCES

- ALCHIAN, A. (1949) An Airframe Production Function. Project RAND Paper.
- ARROW, K. J. (1962) The Economic Implications of Learning by Doing. *The Review of Economic Studies*, 29, 155-173.
- BRAGA, A. F. B., MOREIRA, S. P., ZAMPIERI, P. R., BACCHIN, J. M. G. & MEI, P. R. (2008) New processes for the production of solar-grade polycrystalline silicon: A review. *Solar Energy Materials and Solar Cells*, 92, 418-424.
- BUDDENSIEK, V., ELLINGHAUS, T., IKEN, J., KOENEMANN, D., THOMAS, T. & WOLF, K. (2010) The sun is shining - but not for everyone. *Sun and wind energy* 11/2010, 128-136.
- COTTRELL, A., NUNN, N., PALFREYMAN, D., URFER, A., SCAIFE, P. & WIBBERLEY, L. (2003) Systems assessment of future electricity generation options for Australia. CCSD, Brisbane.
- DUTTON, J. M. & THOMAS, A. (1984) Treating progress functions as a managerial opportunity. *The Academy of Management Review*, 9, 235-247.
- ENERGY EFFICIENCY AND RENEWABLE ENERGY (2010) 2008 Solar Technologies Market Report. Washington DC, United States Department of Energy.
- EUROPEAN PHOTOVOLTAICS INDUSTRY ASSOCIATION (2010) <http://www.epia.org/>.
- GRAHAM, P. W., REEDMAN, L. J. & POLDY, F. (2008) Modelling of the future of transport fuels in Australia: a report to the Future Fuels Forum. Campbell, ACT, CSIRO.
- GRAHAM, P. W. & WILLIAMS, D. J. (2003) Optimal technological choices in meeting Australian energy policy goals. *Energy Economics*, 25, 691-712.
- HAYWARD, J. A., GRAHAM, P. W. & CAMPBELL, P. K. (2011) Projections of the future costs of electricity generation technologies: an application of CSIRO's Global and Local Learning Model (GALLM). CSIRO.
- HIRSCH, W. Z. (1956) Firm Progress Ratios. *Econometrica*, 24, 136-143.
- IKEN, J. (2011) Global overcapacity with regional gaps. *Sun and wind energy*, 1/2011, 122-124.
- IKEN, J., GARUS, K. & BUDDENSIEK, V. (2010) Sober calmness in the industry. *Sun and wind energy*, 11/2010, 96-101.
- INTERNATIONAL ENERGY AGENCY (1993-2009) Trends in Photovoltaic Applications. <http://www.iea-pvps.org/index.php?id=92>.
- INTERNATIONAL ENERGY AGENCY (2000) Experience curves for energy technology policy. Paris, France OECD.
- INTERNATIONAL ENERGY AGENCY (2000-2009) Wind Annual Report. http://www.ieawind.org/AnnualReports_PDF/2009.html.
- JÄGER-WALDAU, A. (2010) PV status report: research, solar cell production and market implementation of photovoltaics. Ispra (VA), Italy, Institute for Energy.
- JUNGINGER, M., FAAIJ, A. & TURKENBURG, W. C. (2005) Global experience curves for wind farms. *Energy Policy*, 33, 133-150.
- KOENEMANN, D. (2010) Proceeding as planned. *Sun and wind energy*, 9/2010, 234-241.
- MILBORROW, D. (2008) Dissecting wind turbine costs. *WindStats Newsletter*, 21, 3-5.
- NEIJ, L. (2008) Cost development of future technologies for power generation-A study based on experience curves and complementary bottom-up assessments. *Energy Policy*, 36, 2200-2211.
- SCHRATTENHOLZER, L. & MCDONALD, A. (2001) Learning rates for energy technologies. *Energy Policy*, 29, 255-261.

- SHUM, K. L. & WATANABE, C. (2008) Towards a local learning (innovation) model of solar photovoltaic deployment. *Energy Policy*, 36, 508-521.
- STAFF OF THE BOSTON CONSULTING GROUP (1968) *Perspectives on Experience*, The Boston Consulting Group.
- VOITH, M. (2009) Solar on sale. *Chemical and Engineering News*, 87, 28-30.
- WRIGHT, T. P. (1936) Factors affecting the cost of airplanes. *Journal of the Aeronautical Sciences*, 3, 122-138.



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Phone: 1300 363 400

+61 3 9545 2176

Email: enquiries@csiro.au

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